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Optical identification of the LMC supersoft source RX J0527.8-6954 from MACHO Project photometry

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ABSTRACT

We identify the likely optical counterpart to the LMC supersoft X-ray source RX J0527.8-6954, and hence recover HV 2554. This identification is based on an analysis of ~ 4 years of optical photometry obtained serendipitously via the MACHO project. We see a steady fading of the star of ~ 0.5 mag over the duration of the observations. Evidence is also presented for an orbital modulation of ~ 0.05 mag semi-amplitude on a period of $P = 0.39262 \pm 0.00015$ d. Our optical observations are consistent with the suggestion that the X-ray decline in this system is caused by cooling after a weak shell flash.

Key words: accretion, accretion discs – binaries: close – binaries: spectroscopic – X-rays: stars – Stars: individual: RX J0527.8-6954

1 INTRODUCTION

The supersoft sources (SSS) are a group of X-ray objects characterised by their extremely luminous ($L_{\rm bol} \sim 10^{38}$ erg s^{-1}) emission at energies < 0.5 keV. The prototypical sources, CAL 83 and CAL 87, discovered by the *Einstein* X-ray observatory (Long, Helfand & Grabelsky 1981), are accreting binaries which share optical similarities with the low mass X-ray binaries (e. g. Pakull et al. 1988; Cowley et al. 1993). Initially, the nature of the compact object remained elusive, with suggestions of both black hole (Cowley et al. 1990) and neutron star accretors existing (Greiner, Hasinger & Kahabka 1991; Kylafis & Xilouris 1993).

However, the model which has gained predominance involves white dwarf primaries accreting at sufficiently high rates ($\dot{M} \gtrsim 10^{-7}$M$_\odot$ yr^{-1}) to sustain steady nuclear surface burning (van den Heuvel et al. 1992). Thus, the extremely soft X-ray emission at near-Eddington limited luminosities is naturally explained. In order to achieve these rates, the donor star is required to be more massive than the white dwarf, so that thermally unstable mass transfer can occur. This model has recently received observational support from optical spectroscopy of the system RX J0513.9-6951, which exhibits collimated outflows at typical white dwarf escape velocities (Southwell et al. 1996).

ROSAT observations have considerably enlarged the

group of supersoft X-ray sources (e. g. Kahabka & Trümper 1996). The object RX J0527.8-6954, discovered in the *ROSAT* first-light observations (Trümper et al. 1991), is a transient SSS, having been undetected in earlier *Einstein* observations. A blackbody fit to the *ROSAT* spectrum (Greiner, Hasinger & Kahabka 1991) indicated spectral parameters very similar to CAL 83. However, continued *ROSAT* monitoring of the source has revealed an exponential decline in the X-ray luminosity by a factor of ~ 50 from 1990-1994 (Greiner et al. 1996), a behaviour currently unique among the SSS to this object.

The identification of the optical counterpart has proved extremely elusive (e. g. Cowley et al. 1993). Greiner (1996) presents a detailed investigation of a search for the Harvard variable star HV 2554, which lies within the X-ray error circle, and is thus a prime candidate. However, he concludes that the variability of this star is questionable, and that no obvious optical signatures are present in any of the resolvable stars within the X-ray error circle (see Fig. 2 of Greiner 1996).

Given the relatively long timescale of the X-ray variability ($\sim$ yrs), it is clearly advantageous to obtain extended optical monitoring over a similar timebase - serendipitously, the MACHO project affords us such an opportunity. Hence, we are able to identify the probable optical counterpart (presumably HV 2554) by looking for long term optical trends in the stars in the X-ray error box, over a period of $\gtrsim 4$ yrs.

2 OBSERVATIONS

The MACHO project (Alcock et al. 1995a) involves nightly monitoring of certain LMC/SMC fields for microlensing events. The LMC supersoft source RX J0527.8-6954 is located in one of these fields, hence we have an optical history of this source since the beginning of the project in August 1992. The observations were made using the 1.27-m telescope at Mount Stromlo Observatory, Australia. A dichroic beamsplitter and filters provide simultaneous CCD photometry in two passbands, a 'red' band ($\sim 6300 - 7600$ Å) and a 'blue' band ($\sim 4500 - 6300$ Å); the latter is approximately equivalent to the Johnson V filter.

The images were reduced with the standard MACHO photometry code SoDoPHOT, based on point-spread function fitting and differential photometry relative to bright neighbouring stars. Further details of the instrumental setup and data processing may be found in Alcock et al. (1995b), Marshall et al. (1994) and Stubbs et al. (1993).

3 RESULTS

We show in Fig. 1 the template image used by the profile fitting routine to determine the resolvable stellar objects in the vicinity of RX J0527.8-6954. Stars which were resolved, and therefore for which there exist individual light curves, are numbered according to the notation of Greiner (1996). We therefore have photometry for all the objects listed 1-9, which lie within the X-ray error circle.

An inspection of the light curves of all these objects revealed interesting variability in Star 6. We should caution that, given the crowded nature of the field and variable seeing conditions, this could be contaminated by light from Star 9. Our definition of "the counterpart" is therefore to be taken as Star 6 or Star 9 - higher resolution time-resolved studies will be required to resolve this ambiguity. However, we note that Greiner et al. (1996) also commented on the apparent variability of Star 6 when compared with the image of Cowley et al. (1993).

3.1 Light curve

We show in Fig. 2 the red and blue photometry of the object flagged as Star 6. The data consists of MACHO project observations taken during the period 1992 August 8 – 1996 November 2. The absolute calibration of the MACHO fields and transformation to standard passbands is not yet complete, thus the measurements are plotted differentially relative to the observed median. One-sigma error bars are shown. A linear fit to each dataset reveals a steady decline of 0.12 mag/yr in the blue and 0.085 mag/yr in the red. Over the time-span of the dataset, which is 4.25 yrs, the optical fading thus amounts to 0.51 mag in the blue and 0.36 mag in the red.

3.2 Period Analysis and Folded Light Curve

The long term decline was removed with a linear fit before performing a power spectrum analysis on the red and blue datasets. We used a Lomb-Scargle technique (Lomb 1976; Scargle 1982) and show the resulting periodograms in Fig. 3. A frequency space of $0.05 - 10$ cycles d^{-1} was searched with a resolution of 0.001 cycles d^{-1}. There is a dominant peak in both datasets at $P = 0.39262 \pm 0.00015$ d, with lesser power at 0.6477 d and 0.28193 d (and 1.838 d in the blue data only). We checked the significance of all the peaks by analysing the power spectra of randomly generated datasets, using the sampling intervals of the real data. Our Monte Carlo simulations reveal that the 0.39262 d period occurs with at least 4-σ confidence in both datasets. In the red data, the remaining peaks occur with only $\sim 1-\sigma$ confidence or less. In the blue data, all four principle peaks represent at least 3-σ detections; however, assuming the stongest peak is the true orbital period (0.39262 d), we note that the 0.6477 d and 0.28193 d periods occur at the values we would expect for one-day aliases, having frequencies which differ by 1 cycle d^{-1} from the dominant peak. Furthermore, the 1.838 d period, (which appears only in the blue data) has a frequency consistent with a two-day alias.

We therefore find strong evidence to suggest an orbital period of $P = 0.39262 \pm 0.00015$ d. The red and blue detrended data were filtered to reject any data points with errors exceeding 0.2 mag. We then folded the remaining points on a period of 0.39262 d to examine the form of any orbital modulation. We find that the blue data are well fitted by a sinusoid of semi-amplitude 0.052$\pm$0.009 mag, suggesting a low inclination. This is shown in Fig. 4. We derive an ephemeris of $\mathrm{T_o} = \mathrm{JD}\,2448843.07(1) + 0.3926(2)E$, where $\mathrm{T_o}$ is the time of maximum optical brightness, and E is an integer.

The fit to the red folded data was less good and is not shown. This is probably due to the larger number of anomalous points in the red light curve (day number $\sim 1300-1500$

in Fig. 2). We have no convincing explanation for these points, there being no indications of particularly bad seeing or instrumental effects which might have accounted for them.

3.3 Long term and orbital colour variation

We investigated the relative MACHO B-R colour as a function of time. Our data indicate a steady reddening of the system, amounting to a total of ~ 0.15 mag over the 1546 days of observations. By removing this long-term trend with a linear fit, and folding the data on $P = 0.39262$ d, we found evidence for a sinusoidal modulation in the B-R colour of semi-amplitude ~ 0.02 mags. These folded data also indicated the system to be reddest at $\phi \sim 0.5$, namely the time of minimum light.

4 DISCUSSION

4.1 Simultaneous optical/X-ray behaviour

During the period 8/8/1992 - 10/8/1995, we may investigate the simultaneous X-ray behaviour using the *ROSAT* data presented in Greiner et al. (1996). The optical decline (in the blue MACHO observations) during this time was 0.36 mags (a factor of ~ 1.4), which may be compared with a decrease by a factor of ~ 5.9 in the X-rays. The system also became redder by ~ 0.1 mag in this time.

Greiner et al. (1996) suggested that the decline in the X-rays represents a decrease in the temperature, following perhaps a weak shell flash. The observed decline in the optical is consistent with such a picture, since some of the optical luminosity is probably produced by the irradiation of the secondary star and the accretion disc by the hot white dwarf. A small decline in the mass transfer rate may also be expected due to the decreased irradiation of the secondary (e.g. Livio 1992). We can obtain a rough estimate of the decay time by examining the Kelvin-Helmholtz timescale of the envelope:

$$\tau_{\rm KH} \approx \frac{GM_{\rm WD}\Delta m_{\rm env}}{R_{\rm WD}L_{\rm WD}}, \qquad (1)$$

where $L_{\rm WD}$ is the luminosity and $\Delta m_{\rm env}$ is the mass of the envelope. If we approximate the envelope mass by that required to produce a thermonuclear runaway on a cold WD (which should be regarded as an upper limit; Yungelson et al. 1995), then we obtain for the decay time: (scaled with the parameter values of a $1M_\odot$ white dwarf),

$$\tau_{\rm decay} \lesssim \tau_{\rm KH} \approx 2300 \text{ days} \left(\frac{M_{\rm WD}}{1M_\odot}\right)^{0.2} \left(\frac{R_{\rm WD}}{7.8\times10^{-3}R_\odot}\right)^{2.2} \left(\frac{L_{\rm WD}}{10^{38}\text{ erg s}^{-1}}\right)^{-1}. \qquad (2)$$

Given the observed decay time in the X-rays of $\gtrsim 5.5$ years (Greiner et al. 1996), this suggests that the WD has a mass of $\sim 1M_\odot$. An examination of the results of Prialnik & Kovetz (1995) also suggests a mass of about $1M_\odot$, if the decay time represents the time for cessation of nuclear burning.

4.2 Binary parameters

Assuming an orbital period of $P = 0.39262$ d, we may calculate the mean density, $\overline{\rho}$, of the companion star under the assumption that it fills its Roche lobe. We combine Kepler's third law and the Eggleton (1983) relation for a Roche-lobe filling star:

$$\frac{R_{L_2}}{a} = \frac{0.49q^{-2/3}}{0.6q^{-2/3}+\ln(1+q^{-1/3})}, \qquad (3)$$

where R_{L_2} is the radius of a sphere with the same volume as the secondary Roche lobe, a is the binary separation, and q is the binary mass ratio ($\equiv \mathrm{M}_{compact}/\mathrm{M}_{secondary}$) to obtain:

$$\overline{\rho} = \frac{0.161}{\mathrm{P}^2(1+q)}\left(0.6+q^{2/3}\ln(1+q^{-1/3})\right)^3 \text{ g cm}^{-3}, \qquad (4)$$

where P is in days. For values of $q \lesssim 1$, as required by the van den Heuvel et al. (1992) model, the implied mean density is ~ 1.1 g cm^{-3}. This is consistent with that of a ~ 1.3 M$_\odot$ main sequence star of spectral type $\sim$ F5 (Allen 1973), although, for the obtained orbital period, the secondary star could be slightly evolved. We estimated the mass of the compact object to be $\sim 1M_\odot$. Hence, values of $q \lesssim 1$, as required by the van den Heuvel et al. (1992) model, are indeed possible if the orbital period assumed here is correct.

5 SUMMARY

We identify the optical counterpart of the supersoft source RX J0527.8-6954 from MACHO Project photometry. A steady fading of $\lesssim 0.5$ mags in the optical light is observed over ~ 4 years. We detect an orbital modulation of ~ 0.05 mag semi-amplitude on a period of $P = 0.39262 \pm 0.00015$ d.

We find the optical fading to be consistent with the model for the X-ray decline suggested by Greiner et al. (1996), in which the system is cooling after a weak shell flash. We estimated the decay time using the Kelvin-Helmholtz timescale of the accreted hydrogen envelope, and obtain a likely white dwarf mass of $\sim 1M_\odot$. Combining this with the inferred mass of the secondary yields a mass ratio which is consistent with the van den Heuvel et al. (1992) model for the supersoft X-ray sources.

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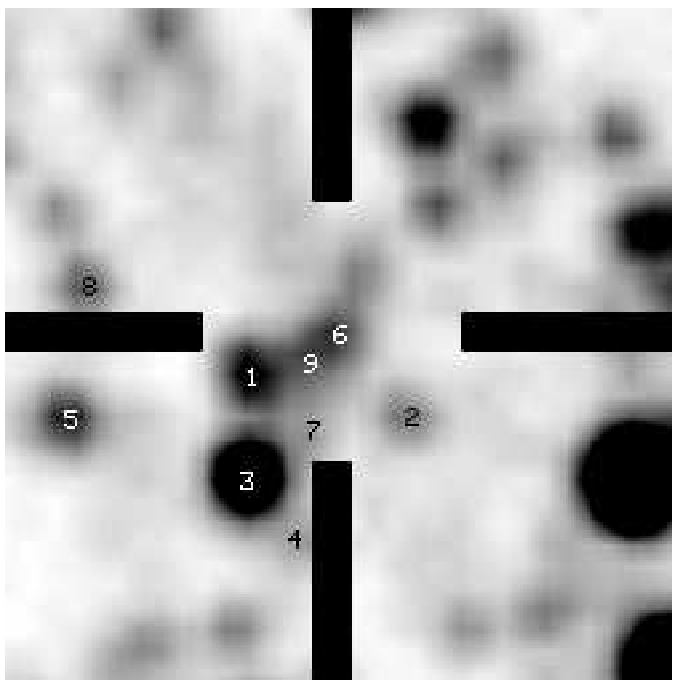
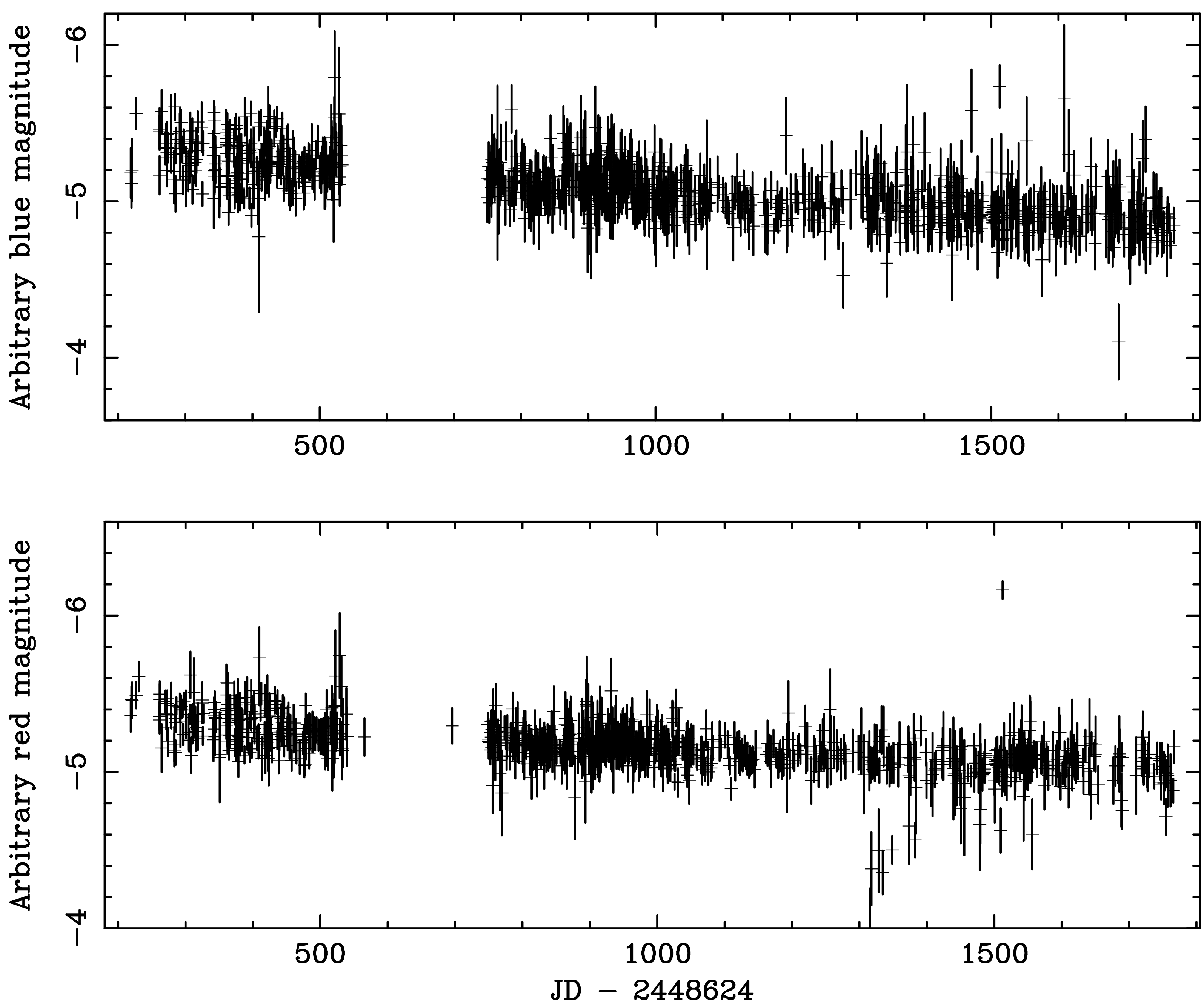
Figure 1. MACHO template image of the field around RX J0527.8-6954, showing stars identified for profile fitting. We resolve the objects listed 1-8 considered by Greiner (1996), and additionally Star 9. North is up, East to the left.

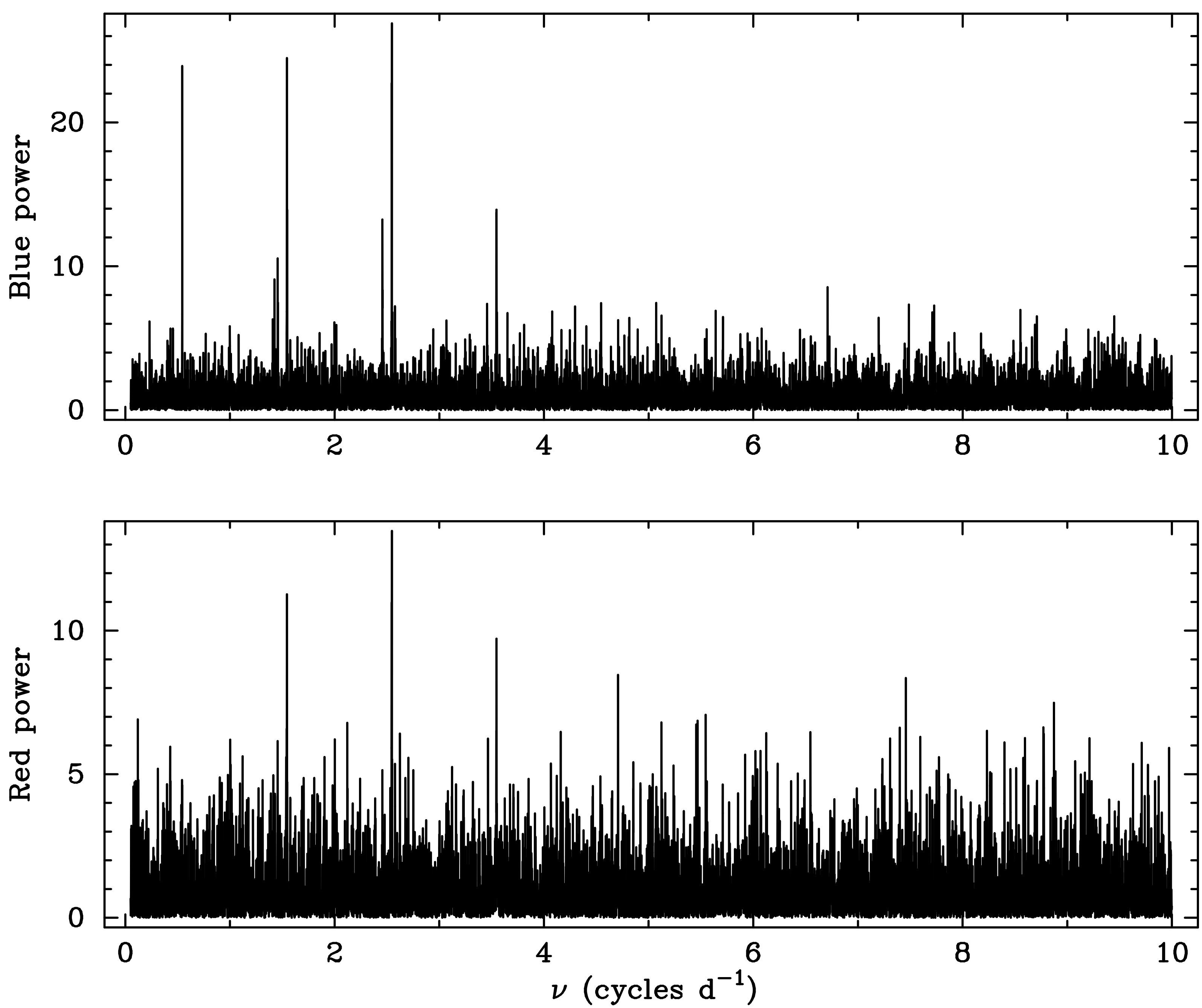
Figure 2. The optical light curve of RX J0527.8-6954 from MACHO project observations. The relative magnitude is shown for the red and 'blue' filters (the latter is approximately equivalent to the Johnson V passband). Note the overall decline in both light curves of ~ 0.5 mag (blue) and ~ 0.4 mag (red) in $\gtrsim 4$ years.

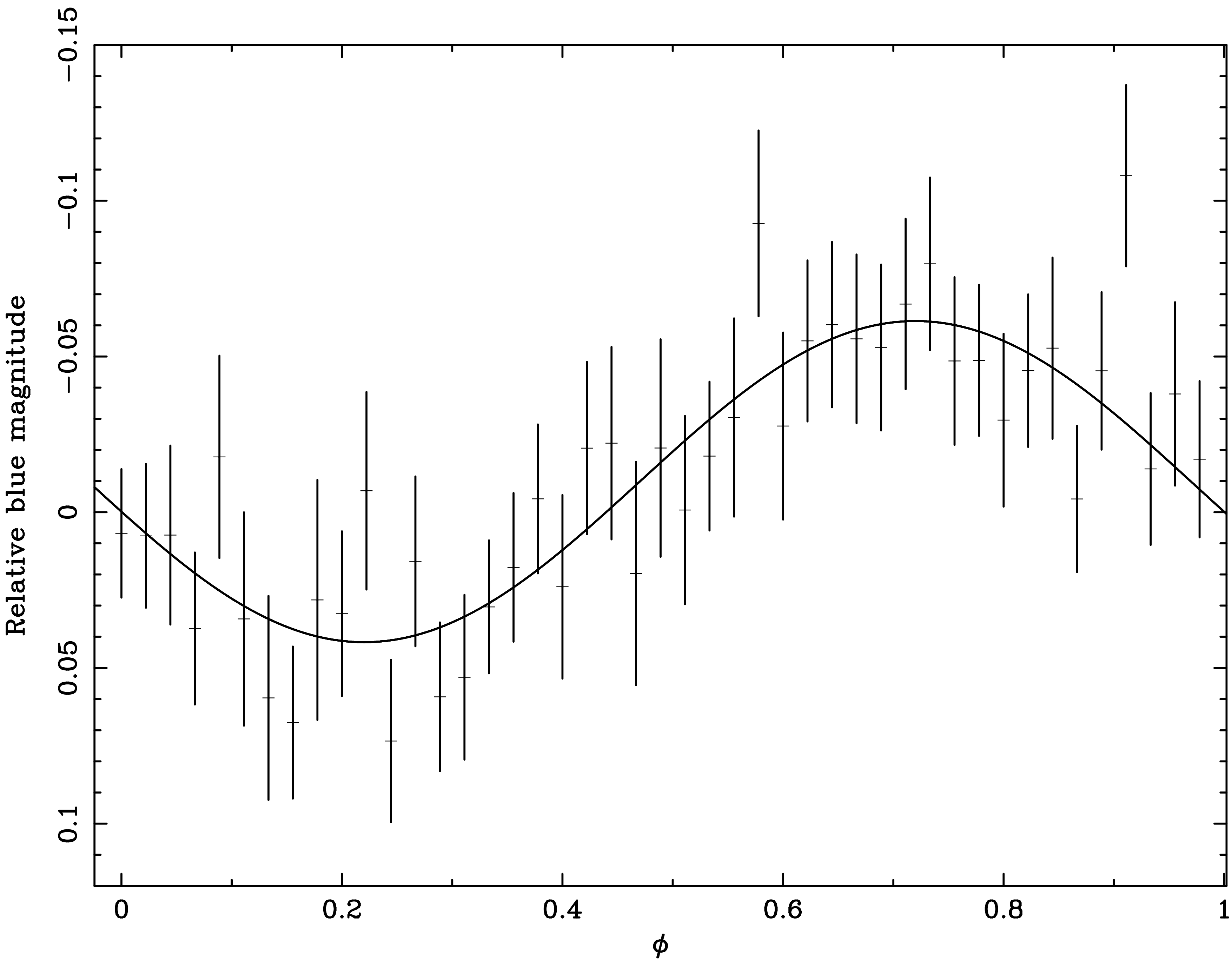
Figure 3. The Lomb-Scargle periodograms of RX J0513-69 MACHO time series data in the blue filter (*upper*) and the red filter (*lower*). The strongest peak is at $P = 0.39262 \pm 0.00015$ d in both datasets.

Figure 4. The blue light curve of RX J0527.8-6954, folded on a period of 0.39262 d. The data have been averaged into 45 phase bins, and are fitted with a sinusoid of amplitude 0.052 mag.


8
6
9
1
5
7
2
3
4


Arbitrary blue magnitude
−6
−5
−4
500
1000
1500
Arbitrary red magnitude
−6
−5
−4
500
1000
1500
JD − 2448624


Blue power
0
10
20
0
2
4
6
8
10
Red power
0
5
10
0
2
4
6
8
10
ν (cycles d⁻¹)



Relative blue magnitude
−0.15
−0.1
−0.05
0
0.05
0.1
0
0.2
0.4
0.6
0.8
1
ϕ